Technical Note: CT Determination of the Mineral Density of Dry Bone Specimens Using the Dipotassium Phosphate Phantom

XINGBIN CHEN[1]* AND Y.M. LAM[2]
[1]*Department of Anatomical Sciences, State University of New York, Stony Brook, New York 11794-8081*
[2]*Doctoral Program in Anthropological Sciences, State University of New York, Stony Brook, New York 11794-4364*

KEY WORDS mineral density; computed tomography; trabecular bone; cortical bone; dipotassium phosphate phantom

ABSTRACT Recent studies have demonstrated the potential application of computed tomography (CT) in research into bone density. Clinical studies of bone density using CT commonly employ a dipotassium phosphate phantom to calibrate measurements of mineral density. Designed for in vivo studies, the use of this phantom requires that bones be scanned while immersed in and permeated by fluids or soft tissues similar to water in X-ray attenuation coefficient. However, this condition may not always be met in anthropological applications, which often involve rare and fragile specimens. This study compares mineral density values calculated for a sample of bones scanned—at the same sites—in air and in water. The results indicate that, when scanned in air, the mineral density of trabecular bone is dramatically underestimated, while that of cortical bone is slightly overestimated. We present a linear regression equation to correct this error but recommend that, when possible, researchers calculate their own regressions based on their specific scanning conditions. Am J Phys Anthropol 103:557–560, 1997.

In the decade since Ruff and Leo (1986) described its potential applications to anthropological research, computed tomography (CT) has been employed in a diverse array of morphological studies (e.g., Daegling and Grine, 1991; Grine et al., 1995; Rafferty and Ruff, 1994; Ruff, 1989; Ruff et al., 1994; Spoor et al., 1993). One such application has been in the determination of bone density, a topic of considerable interest to functional morphologists and physical anthropologists. The adaptability of bone tissue to its loading environment, long the subject of scientific investigation (e.g., Meyer, 1867; Wolff, 1870), has been observed to correspond with changes in bone density. Several recent studies have addressed this apparent relationship between bone density distribution and activity patterns in a number of primate species. For example, Rafferty and Ruff (1994) have studied the differences in the density of subarticular trabecular bone of the humeral and femoral head in three primate species: *Hylobates syndactylus, Colobus guereza,* and *Papio cynocephalus.* Elke et al. (1995) observed distinctive trabecular patterns in the human femoral head and neck. Patterns of bone density distribution have also been used to infer the locomotor behavior of early hominid species (e.g., Lovejoy, 1988; Stern and Susman, 1991).

Three noninvasive methods have traditionally been employed in bone density studies. Conventional X-ray imaging is probably the most widely used method but provides only a gross visual assessment of density

Contract grant sponsor: NSF; Contract grant number 9600889.
*Correspondence to: Xingbin Chen, Department of Anatomical Sciences, State University of New York, Stony Brook, NY 11794-8081. E-mail: chenx@panda.anat.sunysb.edu
Received 2 December 1996; accepted 31 May 1997.

differences. Photon absorptiometry has been commonly and successfully employed in quantitative, longitudinal studies. Its primary drawback is its inability to exclude intraosseus space, such as the medullary cavity, in its calculations of volume, which results in the underestimation of the mineral density in certain skeletal elements. This study is concerned with the third method: quantitative computed tomography. Although this technique has been utilized in anthropological studies for the analysis of cross-sectional geometry, three-dimensional reconstructions, and linear measurements of cortical bone and tooth enamel (e.g., Jungers and Minns, 1979; Daegling, 1989; Daegling and Grine, 1991; Demes et al., 1990; Conroy and Vannier, 1984; Spoor et al., 1993), it has only recently been used for the quantification of bone density in nonhuman primates.

CT measures X-ray attenuation from numerous directions to construct a detailed cross-sectional image of a scanned object (Cann, 1988). CT images are visual representations of X-ray attenuation coefficients, which are expressed as CT numbers or Hounsfield units on a linear scale (Hounsfield, 1973) defined by two points: −1,000 for the attenuation of dry air and 0 for that of pure water at 25°C (Cann, 1988). Because the attenuation coefficient of bone reflects its mineral content, CT numbers correspond with bone mineral density. When appropriate calibration phantoms are used, research has shown CT to produce accurate and reproducible results in its determination of bone mineral density (Cann, 1988; Cann and Genant, 1980). More detailed descriptions of CT and its applications are provided elsewhere (e.g., Cann, 1988; Ruff and Leo, 1986).

For the past two decades, CT imaging has been widely applied in clinical situations to examine osteoporosis-related symptoms (see references in Cann and Genant, 1980); its use is well established for in vivo conditions. In many such studies, CT numbers are converted to mineral density values by calibrating them with the use of a dipotassium phosphate (K^2HPO^4) phantom (Cann, 1988; Cann and Genant, 1980). This phantom, manufactured by Quantitative Technologies, Inc. (San Francisco, CA), consists of five parallel cylindrical chambers which contain solutions of dipotassium phosphate of differing but known concentrations. With these different solutions, a regression equation can be created to convert CT numbers into mineral density values. However, one requirement of this technique is that bone specimens be immersed in and permeated by fluids or soft tissues that are similar to water in X-ray attenuation coefficient. Although inherent to clinical in vivo studies, this requirement cannot always be fulfilled in anthropological studies, particularly those involving fragile museum specimens. This study presents a regression equation for correcting the mineral density values obtained from CT scans of dry bone.

MATERIALS AND METHODS

A GE High Speed Advantage scanner (Waukesha, WI) was used with imaging parameters set at 120 Kv and 280 mA, with a 1 mm scan thickness and a 20 cm field of view. Dry and clean human femora were physically sectioned before scanning in order to accelerate the permeation of water during the phase of the study that required immersion. The bones were secured to the bottom of a plastic basin, which was placed on a cushion of gel pads over a standard Quantitative Technologies calibration phantom. The specimens were first scanned in air and then rescanned at the same locations after the basin was filled with water. A total of 40 sections, both trabecular and cortical, were scanned. The resulting CT images were imported onto a Sun Microsystems (Mountain View, CA) SPARCstation. Using the software 3DVIEWNIX developed by the Medical Image Processing Group at the University of Pennsylvania, the CT numbers of the images were examined and averaged for each bone section. Average CT numbers for four of the five chambers in the phantom (excluding the one specific to soft-tissue studies) were used to calculate the following regression equation to derive values for bone mineral density:

$$y = 0.691x - 19.781$$

where x is the average CT number and y is bone mineral density in milligrams per mil-

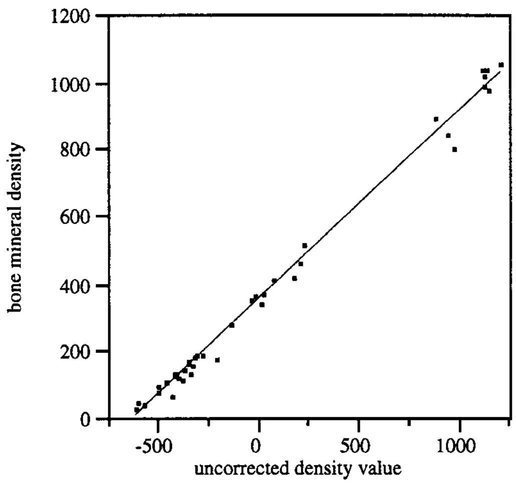

Fig. 1. The relationship between density values (mg/ml) calculated for the specimens scanned at the same locations in air (uncorrected density value) and in water (bone mineral density).

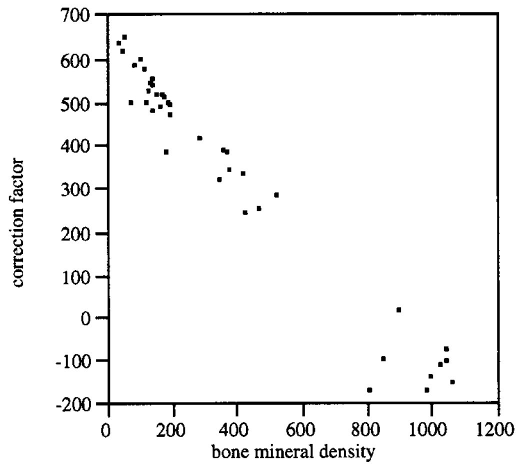

Fig. 2. Bone mineral density (mg/ml) vs. the correction factor (see text for definitions).

liliter. The mineral density was then calculated for each of the 40 bone sections scanned in water and in air.

RESULTS AND DISCUSSION

In meeting the criteria established for the use of the dipotassium phosphate phantom, the bone sections scanned in water are considered to provide accurate mineral density values. A highly significant linear relationship occurs between calculated mineral density values for bones scanned in water and those scanned in air (Fig. 1). The least-squares regression equation ($R^2 = 0.992$, $F = 4884.068$, $P < 0.0001$) is

$$y = 0.563x + 359.607$$

where x is the uncorrected bone mineral density value (i.e., sections scanned in air) and y is bone mineral density (i.e., scanned in water). A correction factor—created for illustrative purposes—represents the difference between bone mineral density and the uncorrected density values. When the bone mineral density is low, as in the case of trabecular sections, the uncorrected dry bone mineral density values consistently and significantly underestimate the actual density (Fig. 2). This underestimation is greatest when the actual density is lowest, resulting in negative values for trabecular sections scanned in air. This observation simply reflects the fact that intraosseous space is occupied by air (CT number = −1,000) during dry scans and by water (CT number = 0) during wet scans. As bone becomes denser and total porosity decreases, the difference between uncorrected and actual bone density becomes smaller until it becomes negligible at approximately 823 mg/ml. However, as bone mineral density further increases (e.g., at middle shaft cross-sections of primarily cortical bone), the uncorrected values from the scanning of specimens in air overestimate the actual density—by as much as 16% in this study. This error is probably due to overcorrection of the beam-hardening effect (Spoor et al., 1993). All CT scanners are capable of correcting the beam-hardening effect that is associated with the progressive diminishing of the lower energy (soft) X-ray beams as they penetrate an object (Cann, 1988; Spoor et al., 1993). When a small object is scanned in a medium that is substantially different in attenuation coefficient, as in this study, the beam-hardening effect may be overcorrected, resulting in elevated CT numbers.

In conclusion, determinations of bone mineral density using the dipotassium phosphate phantom will significantly underestimate the density of trabecular bone and slightly overestimate that of cortical bone if the bone subjects are dry and scanned in air.

In anthropological studies where specimens must be scanned in air, we recommend that researchers determine the relationship—under their specific scanning conditions—between density values derived from scans in water and those from scans in air. This relationship may vary between scanners and between energy levels on the same scanner but can be readily determined by comparing a series of sections scanned in water and in air, as illustrated in this study. If this is not possible, the regression equation presented above may be used as an approximate correction for the density values of bones scanned in air.

ACKNOWLEDGMENTS

We are grateful to Christopher Cann for his technical advice and the contribution of the calibration phantom. We thank Brigitte Demes, Jack Stern, and an anonymous reviewer for their comments on an earlier draft of this manuscript. X.C. acknowledges the support of NSF grant 9600889 and the Department of Anatomical Sciences, SUNY Stony Brook. Y.M.L. acknowledges the support of a Social Sciences and Humanities Research Council of Canada doctoral fellowship and a SUNY Graduate Council fellowship.

LITERATURE CITED

Cann CE (1988) Quantitative CT for determination of bone mineral density: A review. Radiology *166:*509–522.

Cann CE, and Genant HK (1980) Precise measurement of vertebral mineral content using computed tomography. J. Comput. Assist. Tomogr. *4:*493–500.

Conroy GC, and Vannier MW (1984) Non-invasive three-dimensional computer imaging of matrix-filled fossil skulls by high-resolution computed tomography. Science *226:*456–458.

Daegling DJ (1989) Biomechanics of cross-sectional size and shape in the hominoid mandibular corpus. Am. J. Phys. Anthropol. *80:*91–106.

Daegling DJ, and Grine FE (1991) Compact bone distribution and biomechanics of early hominid mandibles. Am. J. Phys. Anthropol. *86:*321–339.

Demes B, Tepe E, and Preuschoft H (1990) Functional adaptations in corpus morphology of Neandertal mandibles. Am. J. Phys. Anthropol. *81:*214.

Elke RPE, Cheal EJ, Simmons C, and Poss R (1995) Three dimensional anatomy of the cancellous structures within the proximal femur from computed tomography. J. Orthop. Res. *13:*513–523.

Hounsfield GN (1973) Computerized transverse axial scanning (tomography): Part I. Description of the system. Br. J. Radiol. *46:*1016–1022.

Grine FE, Jungers WL, Tobias PV, and Pearson OM (1995) Fossil *Homo* femur from Berg Aukas, northern Namibia. Am. J. Phys. Anthropol. *97:*151–185.

Jungers WL, and Minns RJ (1979) Computed tomography and biomechanical analysis of fossil long bones. Am. J. Phys. Anthropol. *50:*285–290.

Lovejoy CO (1988) Evolution of human walking. Sci. Am. *259:*118–125.

Meyer GH (1867) Die Architektur der Spongiosa. Arch. Anat. Physiol. Wiss. Med. *34:*615–628.

Rafferty K, and Ruff CB (1994) Articular structure and function in *Hylobates*, *Colobus*, and *Papio*. Am. J. Phys. Anthropol. *94:*395–408.

Ruff CB, and Leo FP (1986) Use of computed tomography in skeletal structure research. Yrbk. Phys. Anthropol. *29:*181–196.

Ruff CB (1989) New approaches to structural evolution of limb bones in primates. Folia Primatol. *53:*142–159.

Ruff CB, Walker A, and Trinkaus E (1994) Postcranial robusticity in *Homo*. III: Ontogeny. Am J. Phys. Anthropol. *93:*35–54.

Spoor CF, Zonneveld FW, and Macho GA (1993) Linear measurements of cortical bone and dental enamel by computed tomography: Applications and problems. Am. J. Phys. Anthropol. *91:*469–484.

Stern JT, and Susman RL (1991) “Total morphological pattern” versus the “magic trait”: Conflicting approaches to the study of early hominid bipedalism. In Y Coppens and B Senut (eds.): Origine(s) de la Bipédie chez les Hominoidés. Paris: Editions du CNRS.

Wolff J (1870) Uber die innere Architektur der Knochen und ihre Bedeutung fur die Frage vom Knochenwachstum. Virchows Arch. A Pathol. Anat. *50:*389–450.